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Exploring the effects of detailed chemical profiles on the adiabatic oscillation spectrum of sdB stars: First Results

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Abstract. We present results of an ongoing study of the pulsational properties of sdB stellar models aimed at exploring the consequences of detailed chemical transitions for radial, p – and g – modes. In particular, we focus on the effects of diffusion at the H-He transition and of He-burning at the convective cores.

We find that diffusion of He and H has a strong impact on the period spectrum of sdBV stars, leading to less efficient mode trapping. Our results also suggest that asteroseismology of sdBV stars might offer a very good opportunity to constrain extra-mixing processes in the He-burning cores of horizontal branch stars.

1. Introduction

Hot subdwarf stars (sdO, sdB) configure an ubiquitous population of stars, which are located in the HR-diagram between the main sequence and white dwarf stars. Most hot subdwarfs are supposed to be He-core burning stars with H-envelopes which are too thin to sustain H-burning. Thus, hot subdwarf stars are identified with stars in the extreme horizontal branch (EHB, see Heber 2009 for an excellent review). While the fate of hot subdwarfs is very clear, they will evolve towards the white dwarf stage avoiding the asymptotic giant branch, their origin is not fully understood. Most hot subdwarf stars are supposed to be formed from red giants that lost almost the entire envelope (either due to close binary interaction, ingestion of substellar companions or rotationally enhanced winds) or He white dwarf mergers (Han et al. 2002, 2003).

The discovery of multiperiodic pulsations in some sdB stars opened the opportunity to sound the interior of hot subdwarf stars with asteroseismological tools. Specifically two main families of pulsators have been discovered within the sdB stars, the rapid pulsators (sdBVr; Kilkenney et al. 2010) discovered by Kilkenney et al. (1997), and the slow pulsators (sdBVs; Kilkenney et al. 2010) discovered by Green et al. (2003). While sdBVr stars show short pulsation periods ($\sim 80 - 400$ s) ascribed to radial modes and non-radial p -modes, sdBVs pulsations (with periods $\sim 2500 - 7000$ s) are associated to non-radial long period g -modes. Pulsations in both groups of variable stars have been explained by the action of the κ -mechanism due to the partial ionization of iron group elements in the outer layers, where these elements are enhanced by the action of radiative levitation (Charpinet et al. 1997; Fontaine et al. 2003). Besides these two main groups, two other types of pulsating stars have been found among hot subdwarfs,

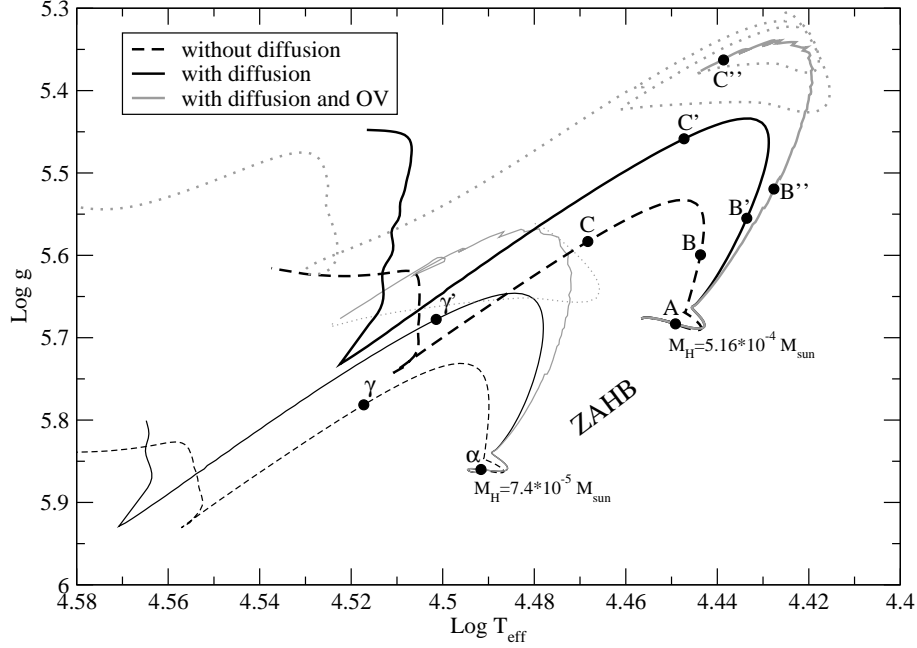


Figure 1. Location in the $T_{\text{eff}} - g$ diagram of the six sequences discussed in this work. Black dots indicate particular models discussed through the text. In particular models A and α correspond to initial ZAHB models for the two different H-envelope masses adopted (thick; $M_{\text{H}} = 5.16 \times 10^{-4} M_{\odot}$, thin; $M_{\text{H}} = 7.40 \times 10^{-5} M_{\odot}$).

the sdOV stars (Fontaine et al. 2008; Randall et al. 2011) with pulsations also driven by the κ -mechanism and the only He-rich sdBV star (LS IV-14°116, Ahmad & Jeffery 2005) which has been recently proposed to be the first observed star with pulsations driven by the ϵ -mechanism (Miller Bertolami et al. 2011).

In the present paper we communicate first results of an ongoing study aimed at understanding the effects of detailed chemical structures on the adiabatic period spectrum of sdB stars.

2. Stellar evolution models and numerical details

The sequences of stellar models presented in this work were computed with LPCODE, a numerical code for solving the equations of stellar evolution, which was already used to model the formation of He-rich subdwarf stars within the hot-flasher scenario (Miller Bertolami et al. 2008). LPCODE is a Henyey-type stellar evolution code designed specifically to compute the whole evolution of low and intermediate mass stars and is described extensively in Althaus et al. (2005) and references therein. Therefore, in what follows, we only refer to the code to mention some particular features of special interest to this work.

In the present work, initial Zero Age Horizontal Branch (ZAHB) models are full evolutionary structures which have been evolved through the helium core flashes at the end of the Red Giant Branch (RGB) (Miller Bertolami et al. 2008). Consequently

the models presented in here are only representative of canonical post-He-flash sdB stars which have a significantly different interior structure to post-non-degenerate sdB models (see Hu et al. 2008). In particular we have followed the evolution of initially $Z = 0.02$ and $M = 0.47426M_{\odot}$ stellar models with two different H-envelope masses (M_{H} ; see Fig. 1) through the He-core burning stage. We computed sequences of models from the ZAHB to the Terminal Age Horizontal Branch (TAHB) under three different physical assumptions (see Fig. 1): 1- Standard stellar evolution models used for reference (no element diffusion, no core overshooting), 2- More realistic stellar evolution models which include the effects of element diffusion, 3- Including the possible consequences of core overshooting at the convective core (also including the effects of element diffusion). Element diffusion was considered only for H, ^3He , ^4He , ^{12}C , ^{13}C , ^{14}N and ^{16}O and computed under the assumption of complete ionization and considering the effects of gravitational settling, thermal diffusion and chemical diffusion but neglecting the effects of radiative levitation (for similar computations that include the effects of radiative levitation of Fe and Ni see Hu et al. 2011). Our treatment of time-dependent element diffusion is based on the multicomponent gas picture of Burgers (1969). Specifically, we solved the diffusion equations within the numerical schemes described in Althaus & Benvenuto (2000) and Althaus et al. (2005). Overshooting was treated as an exponentially decaying diffusive process with a free parameter $f = 0.015$, following Herwig et al. (1997).

Radial and non radial adiabatic oscillations were computed with an updated version of the pulsation code described in Córscico & Althaus (2006).

3. *g*-modes: Effects of H/He-diffusion and core overshooting.

The upper panels of Fig. 2 display the period spacing against period properties of models computed from a same initial model (model A, see Fig. 1) but under different assumptions during the He-core burning evolution. Specifically, we considered two sequences, one that includes the effects of H/He-diffusion in the envelope and one without any diffusion. In agreement with Hu et al. (2009) H/He-diffusion leads to a broadening of composition gradients and less efficient mode trapping (see Fig. 3), as found to happen in pulsating white dwarfs (Córscico et al. 2001). The impact of H/He-diffusion on the Brunt-Väisälä frequency can be clearly appreciated in the lower panel of Fig. 3 in the broadening and flatening of the outermost peak, which is located at the base of the H-rich envelope. Notice also the effect of the H-He transition in the location of the nodes of the mode eigenfunctions (Fig. 3). Note that the effect of diffusion is already apparent early on the horizontal branch evolution, by the time only one third of the original He has been burnt — $\text{He}_{\text{central}} \sim 0.6$, Fig. 2, upper left panel, models B and B' of Fig. 1. The effect of diffusion is even more noticeable close to the TAHB, by the time the central He content has dropped to $\text{He}_{\text{central}} \sim 0.05$ —Fig. 2, upper right panel, models C and C' of Fig. 1. While the model evolved with diffusion displays almost no trapping features, the effects of mode trapping in the $\Delta P - P$ values of the model evolved without diffusion are apparent. It is clear that the effects of H and He diffusion on the chemical profile of sdB stars can not be neglected for detailed asteroseismological fits of observed periods in sdBVs stars. In this connection, it is worth noting the recent determination by Reed et al. (2011) that mode trapping in real stars must be substantially lower than what static models without H/He-diffusion (Van Grootel et al. 2010) indicate. Then the results presented by Reed et al. (2011) might be just indicating the

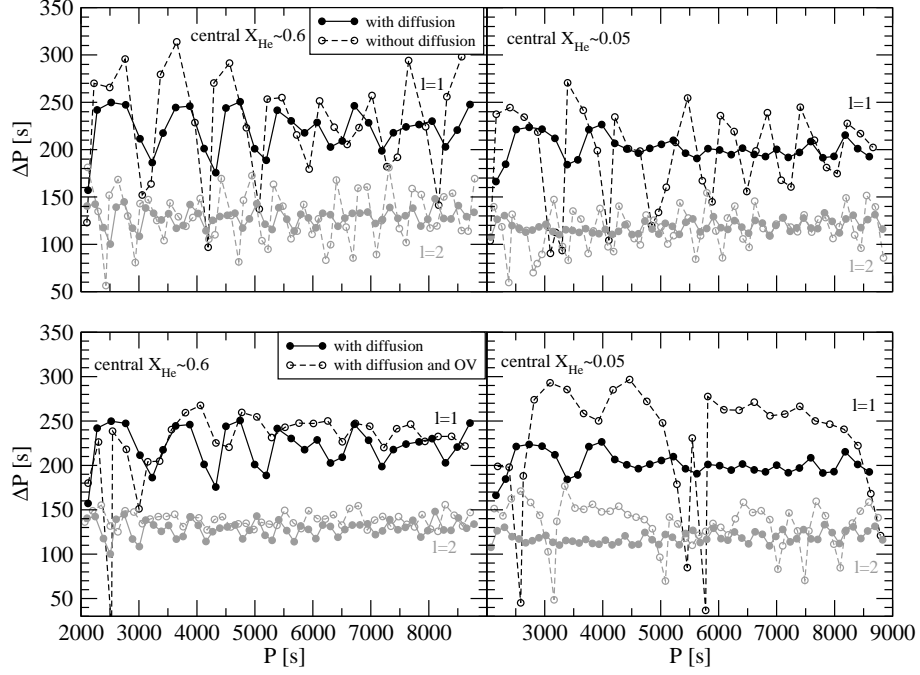


Figure 2. *Upper Panels:* Period spacing properties of g -modes for the models with (solid lines) and without (dashed lines) diffusion for $\ell = 1$ (black) and $\ell = 2$ (grey). Left panel corresponds to models B and B' early on the HB, when the central content of He is still high ($X_{\text{He}} \sim 0.6$), while right panel corresponds to models C and C', close to the TAHB ($X_{\text{He}} \sim 0.05$). Note the nearly equally spaced periods that occur in models that include diffusion due to the absence of strong mode trapping at the H-He transition. *Lower Panels:* Same as upper panels but comparing models with and without overshooting (OV) at the He-burning core (right panel: models B' and B'', left panel: models C' and C''). Note the strong deviations from uniform spacing that occur in the model that includes overshooting due to the complex chemical profiles at the outer boundary of the He-core (lower right panel).

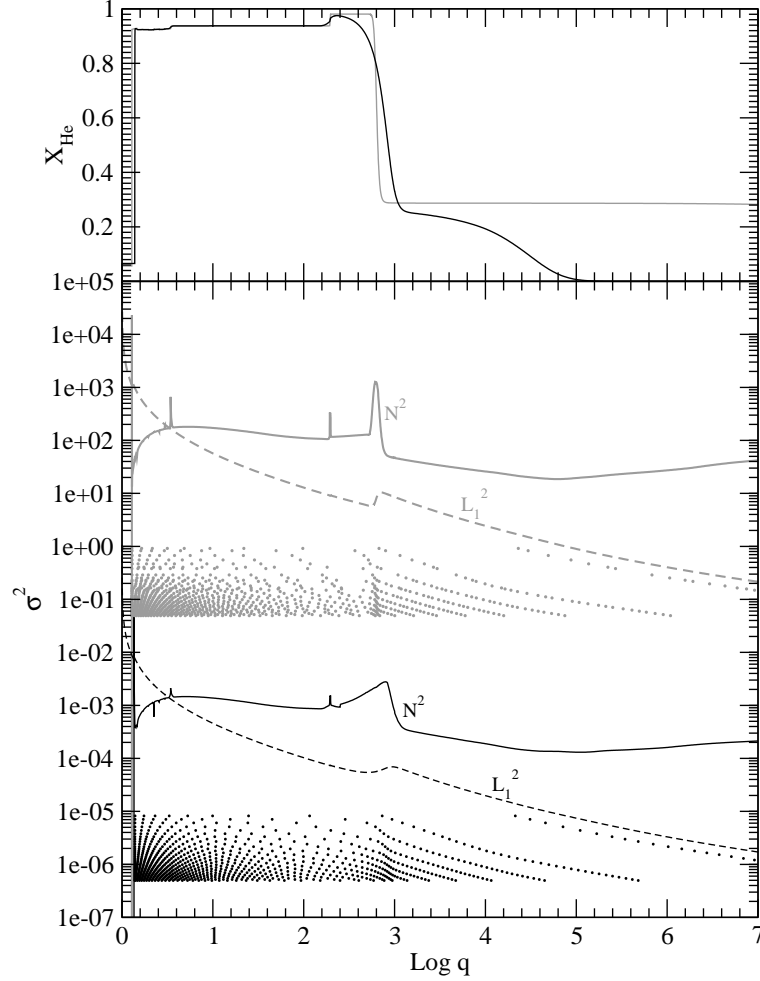


Figure 3. Properties of the models with (black) and without (grey) diffusion close to the TAHB (models C, C'). *Upper Panel:* He profiles of the models. Note the steep profile present in the model without diffusion which causes strong mode trapping. *Lower Panel:* Brunt-Väisälä and Lamb frequencies of the models. Dots indicate the location of the nodes of adiabatic modes at different frequencies within the range of periods shown in Fig. 2. Frequencies for the model without diffusion have been arbitrarily multiplied by 10^5 to avoid overlapping. Note the strong mode trapping that is apparent at the H-He transition in the model without diffusion (grey).

need to include H/He-diffusion in the structures used in asteroseismological determinations of sdB stars (see also Hu et al., Reed et al. these proceedings). If this is so, fully evolutionary models which include diffusion in a selfconsistent way (like those already presented by Hu et al. 2011) might be necessary in order to perform asteroseismological studies of sdBV stars.

In order to explore to what extent the core chemical structure and size impact mode trapping and, thus the period spacing of sdBVs stars, we computed models which include, in addition to the effects of diffusion, overshooting at the convective core. Besides staying longer in the horizontal branch and being more luminous due to a larger He-burning convective core, models that include exponentially decaying overshooting also develop complex step-like chemical profiles at the outer convective boundary (see upper panel of Fig. 4). These chemical transitions have a strong impact on the Brunt-Väisälä frequency (N , e.g. Fig. 4 lower panel). Note, in particular, that g -modes in the range of periods observed in sdBVs stars have several nodes in the region of the star where this step-like chemical profile is located (Fig. 4 lower panel). Thus, we expect the g -mode period spacings of our model to be sensitive to the details of the chemical transition at the outer boundary of the CO-rich core. This is clearly shown by the lower panels of Fig. 2 where we compare the $\Delta P - P$ values of the models evolved with overshooting (B'', C'' which have a complex Brunt-Väisälä frequency at the core boundary) and without overshooting (B', C' which has a relatively simple Brunt-Väisälä frequency at the core boundary). Then, it might be possible to use periods of sdBVs stars to constrain not only the location (as already done by (Van Grootel et al. 2010)) but also the shape of the outer boundary of the He-burning convective core. It is then worth noting that, as the extent of extramixing processes at the He-burning convective core of horizontal branch (HB) stars is not well constrained, sdBVs asteroseismology might be extremely useful tool to learn about the convective cores of the whole population of HB stars.

4. p -modes and radial modes: H-He diffusion and realistic ZAHB H profiles.

Fig. 5 displays the $\Delta\nu$ - ν properties for $\ell = 0$ and $\ell = 1$ modes of models close to the end of the TAHB (Fig. 1, models C, C', γ , γ') computed with and without chemical diffusion and with two different H-envelope thicknesses. As can be clearly appreciated, in both panels of Fig 5, microtrapping features are significantly eroded at high frequencies and the effect is even noticeable for low order acoustic modes within the range of periods of sdBVs pulsators ($\nu < 12$ mHz). This is caused by the smoothing of the H-He transition which affects not only the Brunt-Väisälä frequency but also Lamb frequencies (L_ℓ) and thus both p and radial modes.

In connection with the trapping features of acoustic modes it is worth noting that stellar evolution computations predict that the shape of the H-He transition depends on the thickness of the H-rich envelope already at the ZAHB (see Fig. 6, models A and α of Fig. 1). Thus, contrary to usual assumptions (e.g. Fig. 33 of Charpinet et al. (2002)), thin envelope models not only have a more external peak in the Brunt-Väisälä frequency but also a smoother peak than thick envelope models. This is true despite the fact that the shape of the chemical transitions are equal in both models in the Lagrangian coordinate ($m(r)$) and is caused by the more expanded envelope of the models with thinner envelopes.

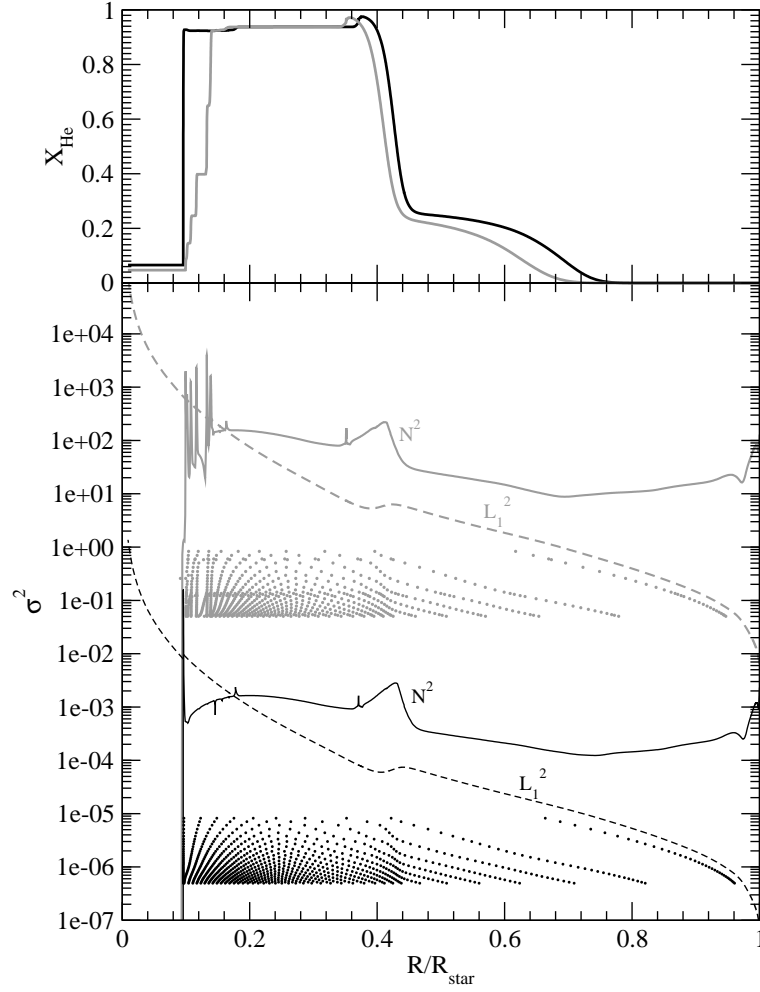


Figure 4. Same as Fig. 3 but for the model (with diffusion) that includes exponentially decaying overshooting compared with the model that only includes diffusion but no extramixing at the convective core (models C' and C''). Note the complex He chemical profile at the outer boundary of the He-burning core (grey, upper panel) that leads to a very complex structure of the Brunt-Väisälä frequency (lower panel). Note the mode trapping caused by these chemical transitions which can be appreciated in the location of the nodes of the model with overshooting (grey dots).

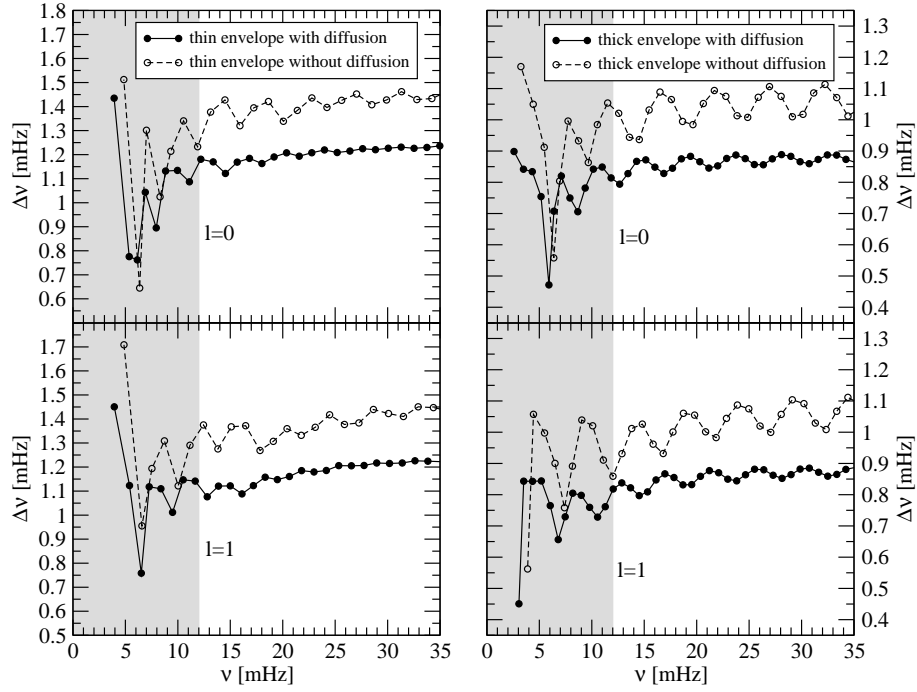


Figure 5. Frequency spacing properties for the models with (solid lines) and without diffusion (dashed lines) close to the TAHB (models γ , γ' , C and C'). Upper (lower) panels correspond to radial modes ($l = 1$ p -modes). Values for the models with thick envelopes (C, C') are shown in the right panels while the left panels display the values for the models with thin H-envelopes (γ , γ'). The grey area correspond to the frequencies observed in sdBVr pulsators.

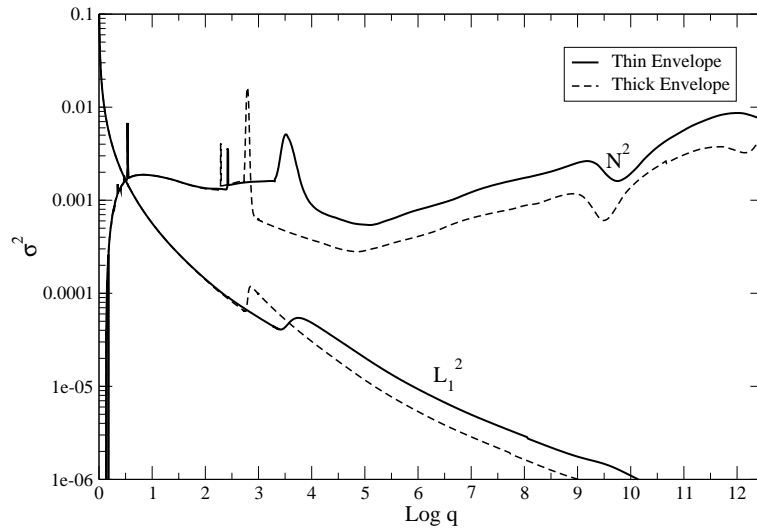


Figure 6. Brunt-Väisälä and Lamb frequencies of initial ZAHB models with thin and thick H-envelopes (A and α). Note the higher peak in the Brunt-Väisälä frequency of the model with a thick H-envelope which will cause stronger mode trapping in thick envelope models even in the absence of diffusion.

The impact of the effect of detailed chemical H-He transitions on seismic envelope mass determinations of sdBVr stars should be explored.

5. Conclusion

We have explored the effects of detailed chemical transitions arising from evolutionary processes on the adiabatic oscillation spectrum of sdBV stars.

Our results show that long period, g -mode, oscillations as those observed in sdBVs stars are affected by H/He-diffusion. In particular we find that the models that include diffusion have periods which are more equally spaced than models which do not include diffusion at the H-He transition. In this context the recent finding of nearly equally spaced periods in sdBVs stars (Reed et al. 2011) might be a strong indication of the occurrence of diffusion at the H-He transition of sdB stars.

Our results also indicate that the details of the chemical transitions at the outer boundary of the He-burning core may affect the mode trapping features in sdBVs stars. This might open a very good opportunity to constrain both the size of the core and the shape of the chemical profiles at the outer boundary of the He-burning core. As extramixing processes at the boundaries of He-burning cores are not well understood or constrained, asteroseismology of sdBVs stars might offer the opportunity to learn about extramixing processes in the cores of horizontal branch stars.

Finally, our preliminary study suggests that the details of the H-He transition might also affect the frequencies of modes in the observed frequency range of sdBVr stars. We think that the impact of realistic H-He transitions in asteroseismological determinations of sdBVr stars should be explored.

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